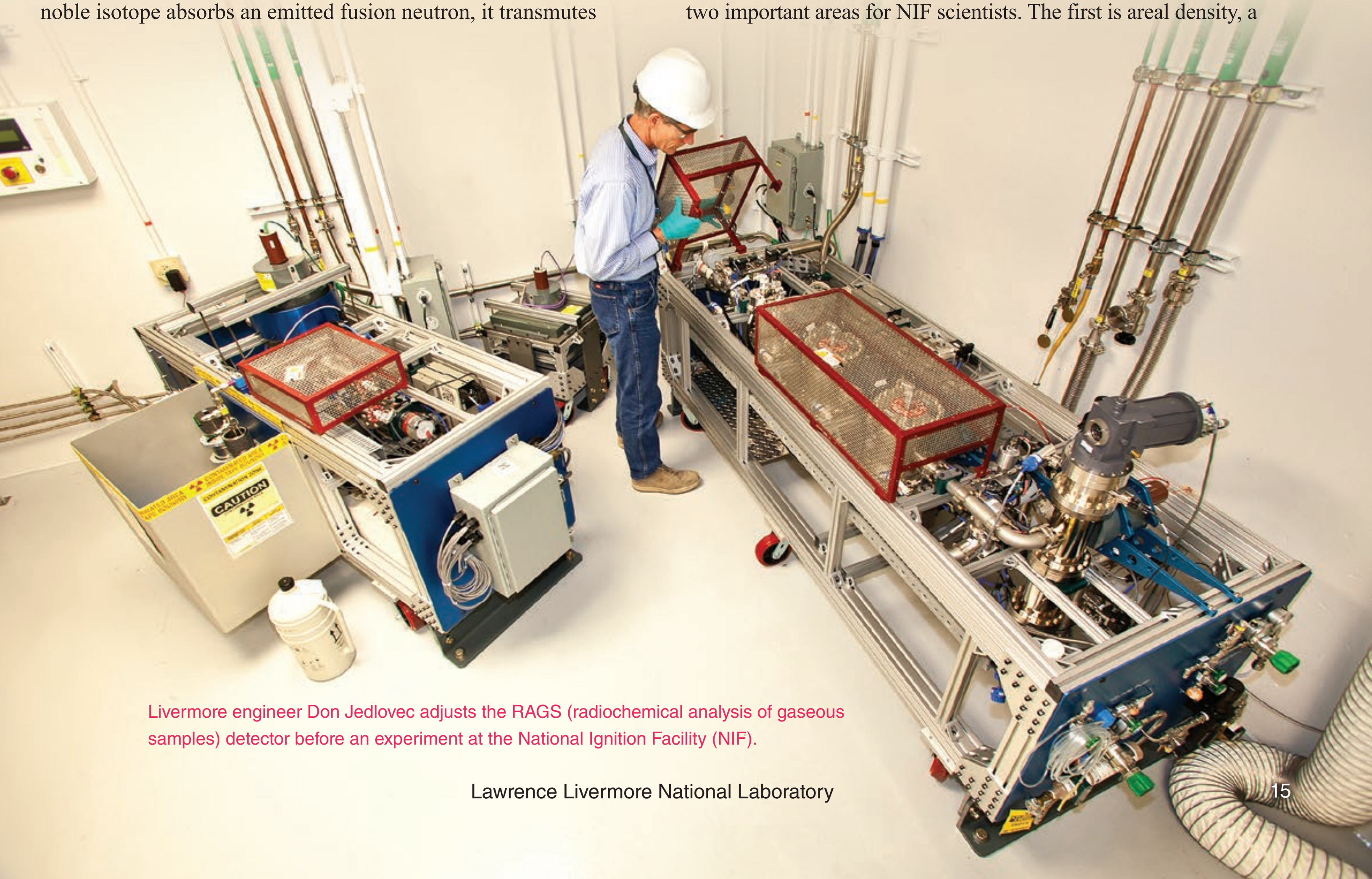
A New Detector for Analyzing NIF Experiments

WHEN the National Ignition Facility's (NIF's) 192 laser beams deliver an enormous jolt of energy and power to a fusion fuel capsule, extremely sensitive, fast, and high-resolution instruments record the data needed to analyze an experiment. A new detector, called RAGS (radiochemical analysis of gaseous samples), collects and analyzes gases produced during an experiment to characterize the results with new data and in greater detail than was previously possible.

The principle behind RAGS is "doping," or implanting, regions of the fuel capsule with a noble gas, a chemically nonreactive element such as xenon, krypton, or argon. During a NIF ignition experiment, atoms of tritium and deuterium (the heavy isotopes of hydrogen) fuse to form a helium nucleus—a reaction that has as a by-product a high-energy neutron. When an atom of a stable noble isotope absorbs an emitted fusion neutron, it transmutes to a different gaseous radioactive isotope. The transmutation can be studied and provides a signature of the fusion reactions in the fuel capsule.

These kinds of nuclear reactions occur during the normal life cycle of stars, offering researchers information about our universe and its history. Livermore physicist Richard Fortner also notes that RAGS mimics radiochemical techniques used in underground nuclear tests before they were discontinued in 1992. In those tests, tracer elements were activated by neutrons generated in the nuclear detonation. Researchers then analyzed the newly synthesized isotopes to determine the temporal and spatial history of the device conditions. "If you want to know what's going on in a particular location, tracer amounts of radioactive materials will tell you," says Fortner, who was the Laboratory's last associate director for nuclear testing.

RAGS joins the close to 60 optical, x-ray, neutron, and gamma-ray diagnostics on NIF designed to provide a virtually complete picture of the fleeting events that occur in an ignition experiment. (See *S&TR,* December 2010, pp. 12–18.) The new detector is one of several neutron diagnostics that together allow researchers to measure neutron yield and temperature, bang time (the interval from laser pulse initiation to maximum neutron emission), and reaction history so they can evaluate how well the target performed. According to Livermore radiation chemist Dawn Shaughnessy, RAGS is particularly useful because it provides information on two important areas for NIF scientists. The first is areal density, a



Livermore engineer Don Jedlovec adjusts the RAGS (radiochemical analysis of gaseous samples) detector before an experiment at the National Ignition Facility (NIF).

measure of the combined thickness and density of the imploding frozen fuel shell. The second is mix, a potentially undesirable condition during which spikes of the plastic rocket shell penetrate to the core of the hot fuel and cool it, decreasing the probability of igniting a sustained fusion reaction with energy gain.

Probing the Density of the Fuel Layer

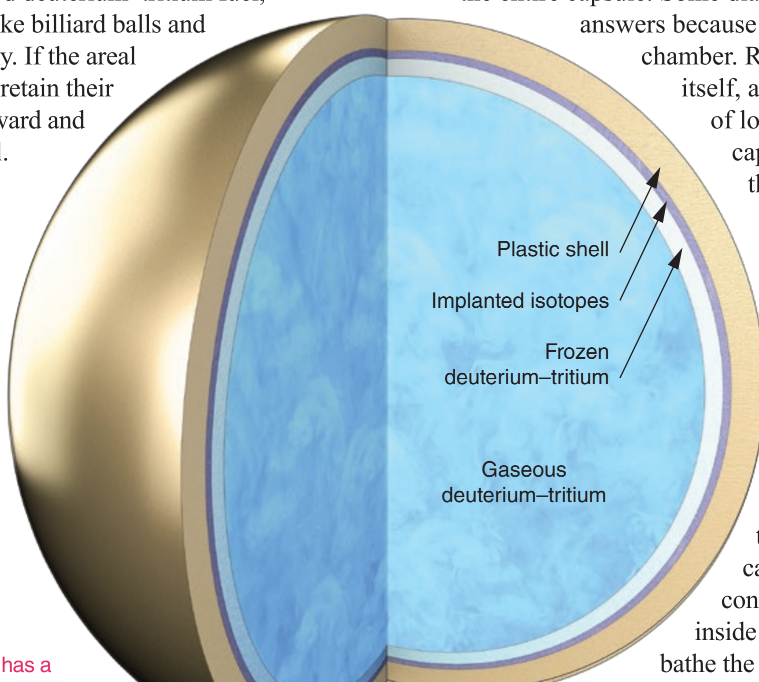
Lee Bernstein, a physicist in Livermore's Physical and Life Sciences Directorate, says, "For ignition to occur, we must prepare the fusion fuel with a high enough areal density and temperature as well as a symmetric shape at the time of peak compression." Over the past year, NIF ignition experiments have demonstrated a steady increase in the areal density by improving the timing and shape of the laser pulse and the symmetry of the compressed fuel.

RAGS is key to accurately measuring the fuel's overall areal density, which has proven to be particularly challenging. When the hydrogen isotopes deuterium and tritium fuse, they generate energetic neutrons along with helium nuclei, which are often called alpha particles. If the areal density is high, many of these neutrons collide with the highly compressed deuterium–tritium fuel, scattering and bouncing around like billiard balls and losing some of their kinetic energy. If the areal density is too low, most neutrons retain their original energy as they travel outward and pass through the thin layer of fuel.

For experiments using RAGS, the innermost 5 to 6 micrometers of the plastic shell next to the frozen deuterium–tritium fuel layer is implanted with atoms of xenon-124. During compression, this isotope will undergo one of two possible transmutations, depending on the energy of the neutron. When a high-energy (about 14.1-megaelectronvolt) neutron is absorbed by an atom of xenon-124, the isotope immediately ejects two neutrons, yielding xenon-123 (which has a 2-hour half-life). When xenon-124 captures a lower-energy (less than 5-megaelectronvolt) neutron, it produces xenon-125 (with a 17-hour half-life).

RAGS collects the xenon gas produced by the experiment, separates xenon-123 and xenon-125, and cryogenically processes the gaseous species in several stages. The first stage removes water vapor, particulates, and reactive gases such as nitrogen, oxygen, and carbon dioxide. The noble gases flow through this precleaner and into the second stage, where a collector cryogenically fractionates (separates) the remaining gases on the basis of their vapor pressures under vacuum and at temperatures near 80 kelvins. Radioactive samples are then transferred to the Laboratory's Nuclear Counting Facility, which measures the gamma rays emitted as the gases decay. The ratio of the two isotopes gives researchers a quantity that is related to the capsule's areal density.

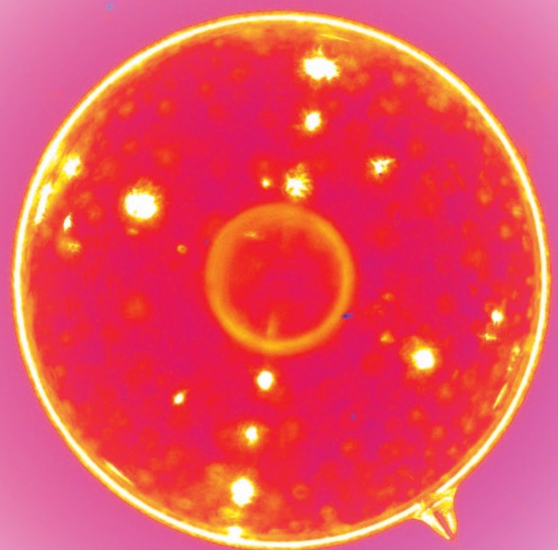
"We want a large ratio of xenon-125 to xenon-123 because that indicates a large areal density," says Shaughnessy. "Because our tracer is inside the capsule, we gain an average areal density from the entire capsule. Some diagnostics appear to give different answers because of their position around the chamber. RAGS is insensitive to the chamber itself, and its performance is independent of location or line of sight into the capsule. In addition, RAGS collects the postshot gas load, so it does not compete for real estate with other diagnostic instruments inside the chamber."



A fuel capsule for ignition experiments has a plastic shell enclosing layers of frozen deuterium and tritium atoms. For experiments using RAGS, the innermost 5 to 6 micrometers of the plastic shell next to the frozen fuel is implanted with atoms of the stable noble gas xenon-124 isotope. When NIF laser beams strike the internal walls of the hohlraum, they are converted to x rays that irradiate the capsule inside. The plastic outer wall rapidly ablates, or burns away, while the adjoining fuel layer implodes and compresses the capsule core. (Rendering by Kwei-Yu Chu.)

Measuring Mix

Researchers at NIF also plan to use RAGS to determine the extent of fuel–ablator mix, a critical measure of an experiment's performance. The ablator is the plastic outer layer of the fuel capsule. In ignition experiments, converging laser beams illuminate the inside of the hohlraum, creating x rays that bathe the fuel capsule inside. The capsule's plastic outer wall is designed to rapidly ablate, or burn away, while the adjoining layer of frozen deuterium–tritium fuel implodes, or compresses, to extraordinarily high temperatures, pressures, and density. Mix occurs when spikes of the plastic ablator shell penetrate the hot burning fuel, thereby cooling it and lowering fusion performance overall. "When ablator material gets into the center of the burning fuel, it is equivalent to dropping ice cubes into a hot drink," says Bernstein.



This microballoon, only 2.1 millimeters in diameter, was used in the exploding pusher shot to commission the RAGS detector. The spherical glass shell was filled with a 50/50 mixture of deuterium and tritium and a small amount of stable xenon-124. RAGS successfully measured the xenon-123 and xenon-125 that were generated when NIF's laser beams hit the target.

Evaluating the extent of mix is difficult because it occurs over a very small area. RAGS offers an elegant way to measure mix because of its sensitivity. In addition, it can reveal the distance over which mix occurs.

Determining how much of the shell penetrates the center depends on detecting certain nuclear reactions. For these measurements, the intersection of the fuel layer and the ablator shell is doped with atoms of iodine-127. A mixture of iodine-127 plus a molecule of deuterium yields xenon-127 plus two neutrons. A high concentration of xenon-127 would thus indicate an undesirable level of ablator–fuel mix.

Conceived at Livermore, Built at Sandia

Several researchers at Lawrence Livermore conceived of the RAGS detector. Physicist Wolfgang Stoeffl worked out the operating design, and Allen Riddle from Sandia National Laboratories (now at Livermore) created the final design. The instrument was built at Sandia's New Mexico site and shipped to Livermore for installation.

In February 2012, RAGS was commissioned during an exploding pusher shot, in which NIF lasers fired 375 kilojoules of energy directly into a microballoon—a 2.1-millimeter-diameter spherical glass shell. The microballoon (shown above) was filled with a 50/50 mixture of deuterium and tritium and a small amount of stable xenon-124. RAGS successfully measured the xenon-123 and xenon-125 created in the implosion.

Shaughnessy notes that data from RAGS complement other NIF instruments such as the neutron time-of-flight (nTOF) detector, which records the neutron energy spectrum, fuel temperature, bang time, and areal density. The nTOF diagnostic measures the energy of the neutron signal based on the time a neutron originates in the capsule to when it arrives at the detector. The travel time is a function of temperature, which is directly related to how fast the fuel capsule implodes. Temperature is critical because, without the right temperature, ignition will not occur.

Three nTOF detectors are installed outside the NIF target chamber at different locations, each about 20 meters from the target. The instruments were calibrated on the OMEGA laser, a 30-kilojoule, 60-beam system operated by the University of Rochester's Laboratory for Laser Energetics. Although nTOF instruments help scientists determine areal density, each one has a limited line of sight. Physicist Jim Knauer from the University of Rochester is combining data from the three instruments to map neutron scattering within the target chamber and determine the detectors' uniformity.

Another device, the neutron activation diagnostic, uses zirconium metal foils, each about 7 centimeters in diameter, positioned on 17 ports around the target chamber to measure the relative distribution of neutrons produced in an ignition experiment. During a shot, neutrons hit and activate the metal foils. The foils are removed and transferred to the Livermore Nuclear Counting Facility, where gamma rays are recorded as the reacted nuclei decay. Using this information, physicist Darren Bleuel and postdoctoral researcher Charles Yeamans create fuel density maps to determine the symmetry of the imploding fuel layer and thereby help physicists plan future experiments.

Combining RAGS data with those from other neutron-sensitive diagnostics provides an in-depth picture of performance within the fusion environment. Together, the NIF diagnostics are yielding unprecedented data about ignition experiments. "With RAGS, we have a new view into the fusion reactions occurring inside the capsule," says Shaughnessy, "and we can obtain information about the extent of mix from the imploding shell into the burn region."

—Arnie Heller

Key Words: alpha particle, areal density, ignition, iodine-127, National Ignition Facility (NIF), mix, neutron time-of-flight (nTOF) detector, radiochemical analysis of gaseous samples (RAGS) detector, stable noble gas, xenon-124.

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